Predicting and Optimizing Building Energy Performance: Why is this so hard?

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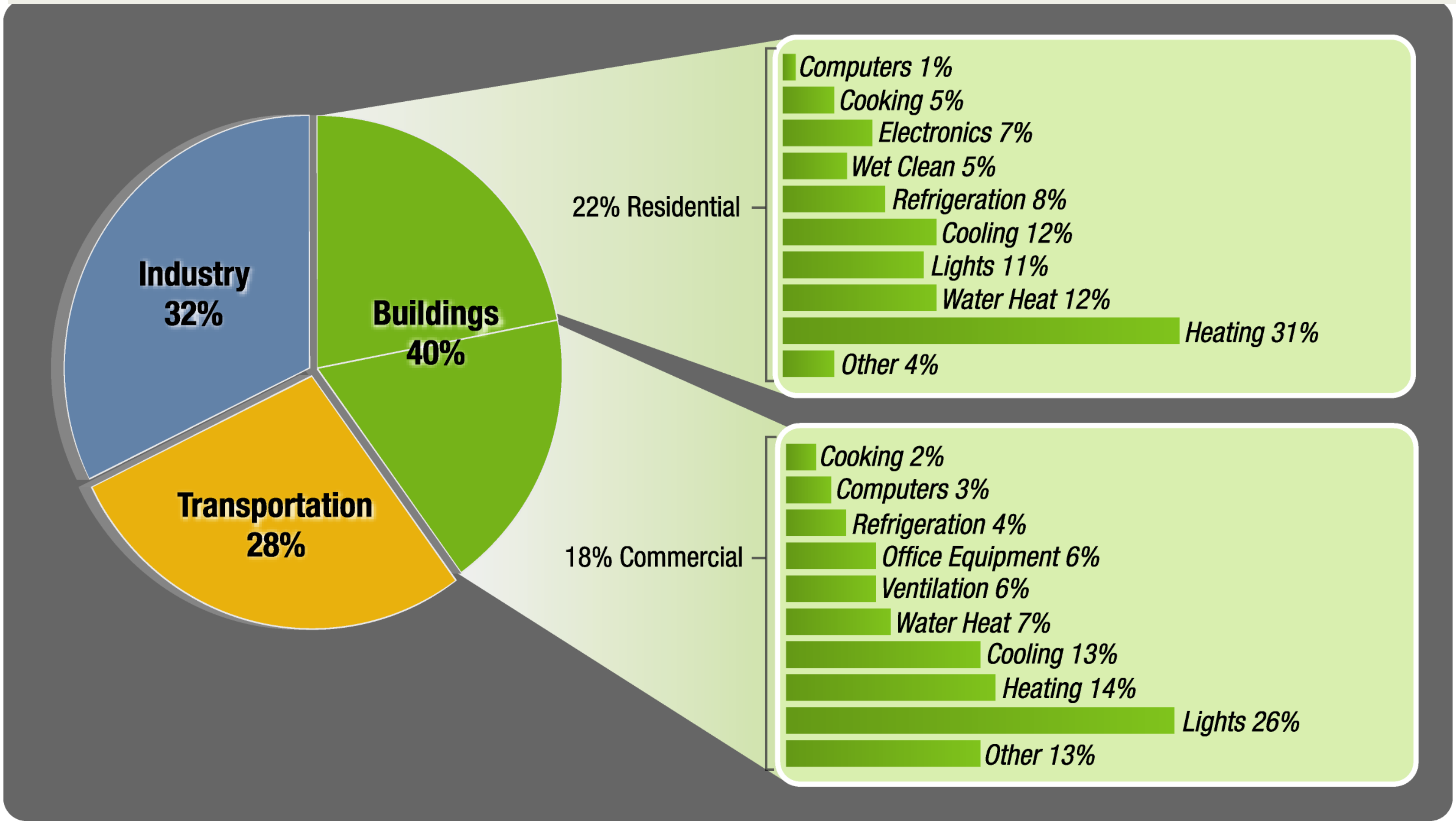
U.S. Buildings' share of Primary Energy

Buildings use 72% of U.S. electricity. 55% of the country's natural gas is used *in* buildings and most of the rest is used to provide electricity *for* buildings.

Building utility bills totaled **$370 Billion** in 2005.

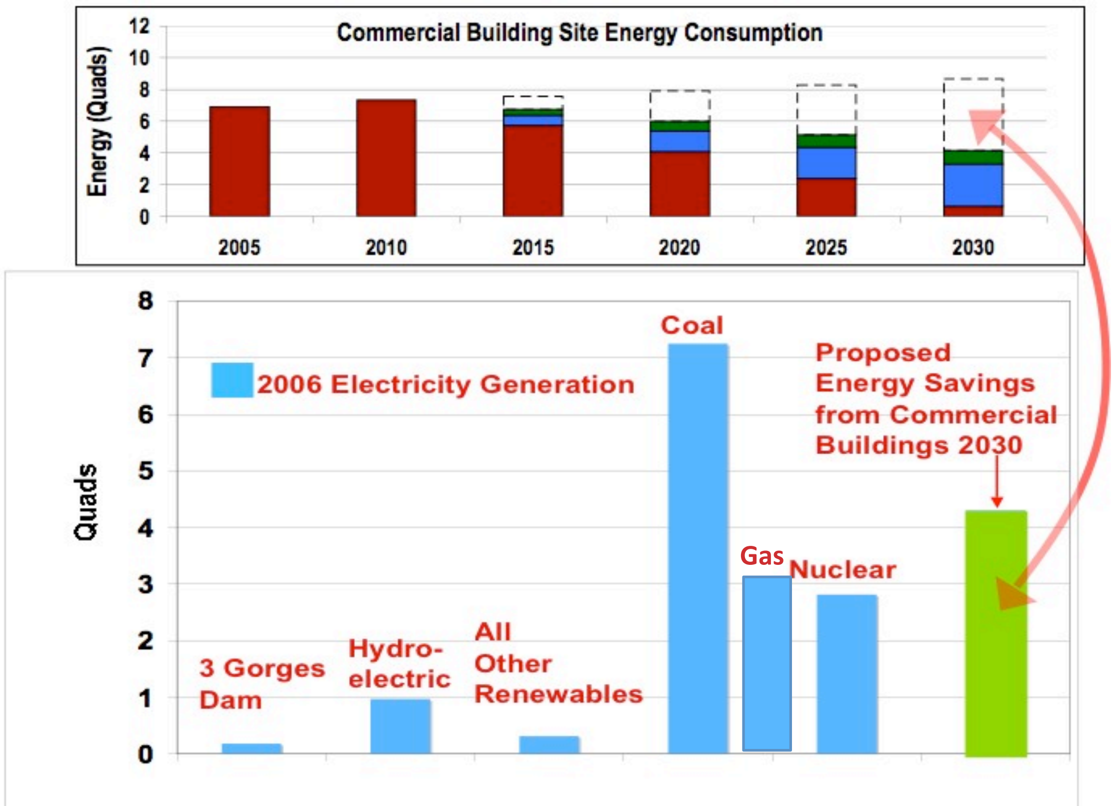


Source: *Buildings Energy Data Book 2007*

LBNL vision for U.S. commercial building stock

Enable transformation of U.S. Commercial buildings sector in 20 years

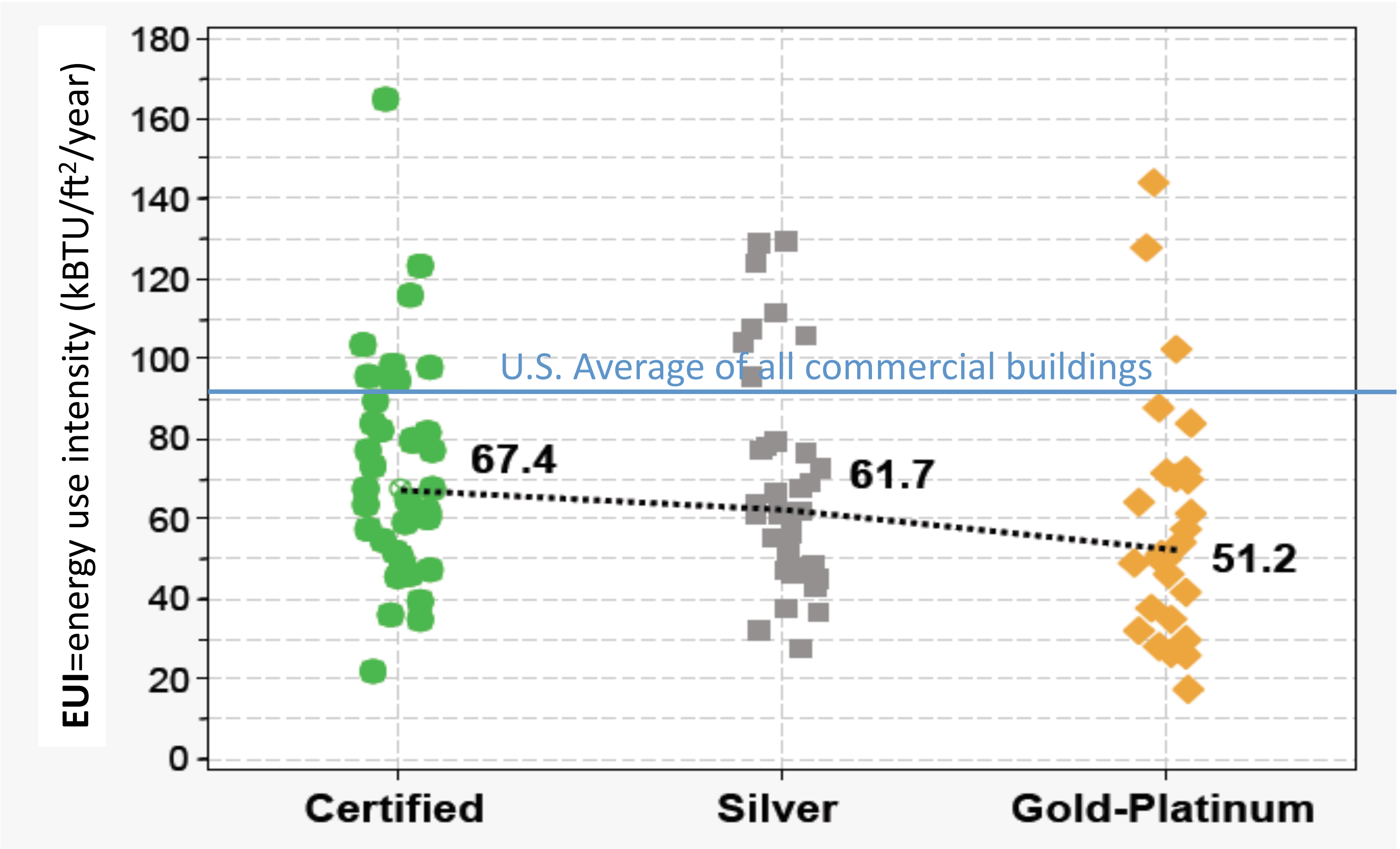
– Save > 4 Quads/y of energy and reduce >400 million tons of CO_2/y by 2030
    - Goal: Reduction in energy consumption: 80% in new buildings; >50% in retrofits
– Enhance health, comfort, safety/security and water usage while gaining energy efficiency



1 Quad/yr = 1 quadrillion BTUs/yr = ~10^{18} J/yr = 3 x 10^{11} kWh/yr = 3.4 x 10^{10} W

Current Status

LEED Buildings

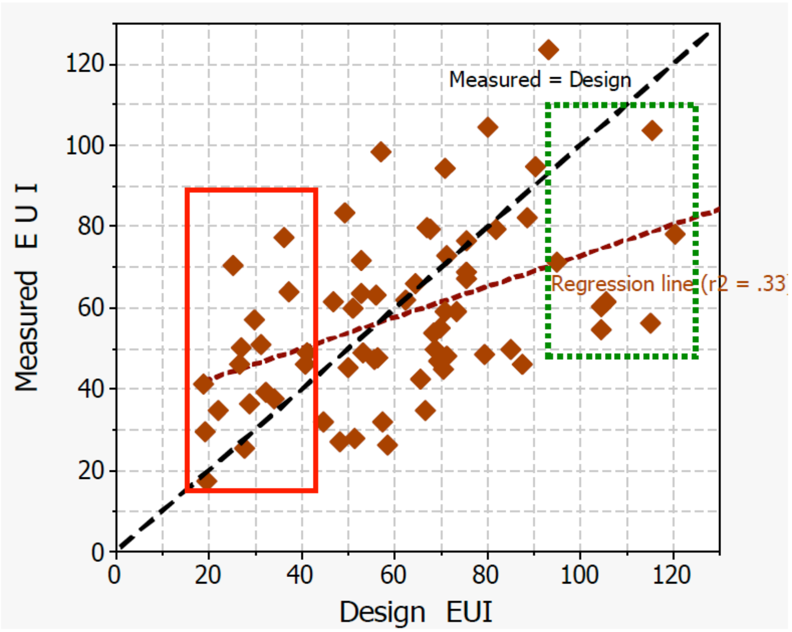


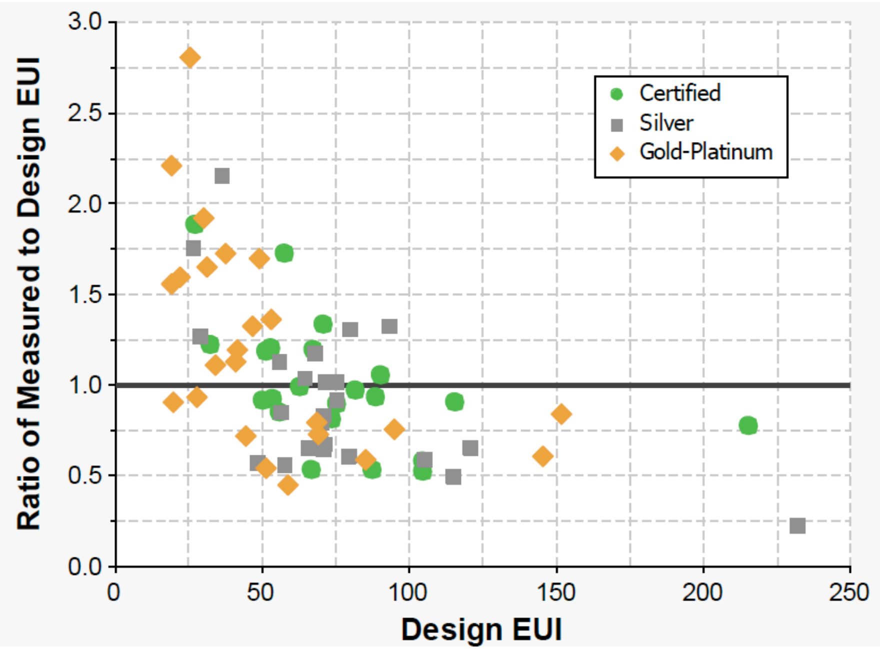
EUI of 60 kBTU/ft^2/year = 0.53 kWh/m^2/day = **22 W/m^2**

Figure Credit: Michael Frankel, NBI, presentation at ACEEE 2008

According to models, very low EUI isn't all that hard…but actual performance of those buildings is much worse than predicted

Analysis of 121 low- to medium-EUI LEED-Rated Buildings





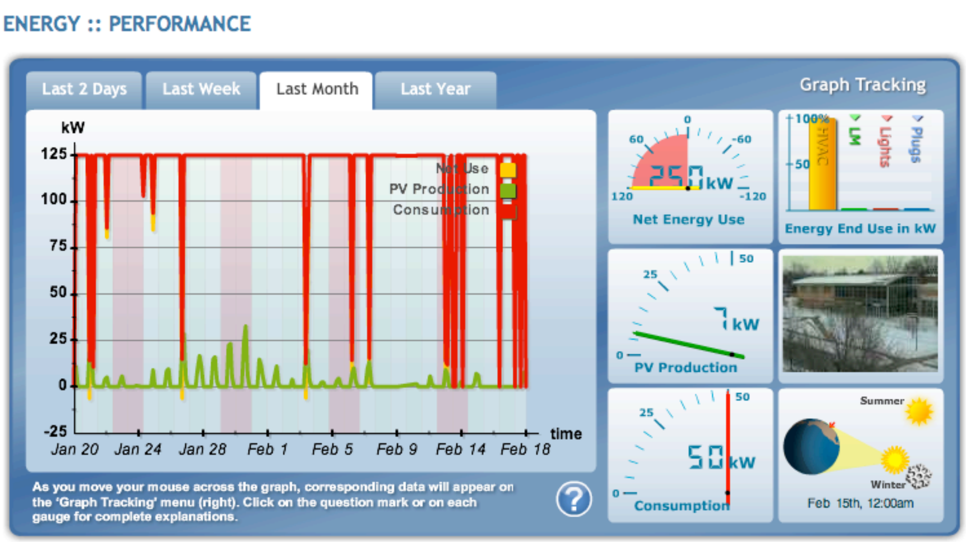
Energy Use Intensity **(EUI)** in kBTU/ft^2/yr (divide by 3 to get W/m^2)

M. Frankel, "The Energy Performance of LEED Buildings,"presented at the *Summer Study on Energy Efficient Buildings, American Council of Energy Efficiency Economy*, Asilomar Conference Center, Pacific Grove, CA, August 17-22, 2008.

“You need building design software…that has, embedded in it, energy analysis, so if you make a change you can predict the performance of the building. So you don’t get the scatterplot [on the previous slide]” - Secretary of Energy Steven Chu, May 2009

Oberlin College Lewis Environmental Center

Photo from "Zelda Go Wild's" flickr photostream, used without permission



Intended to be Net Zero Energy (production = demand)

14,000 square feet, two stories
Classrooms, offices, auditorium, "living machine"

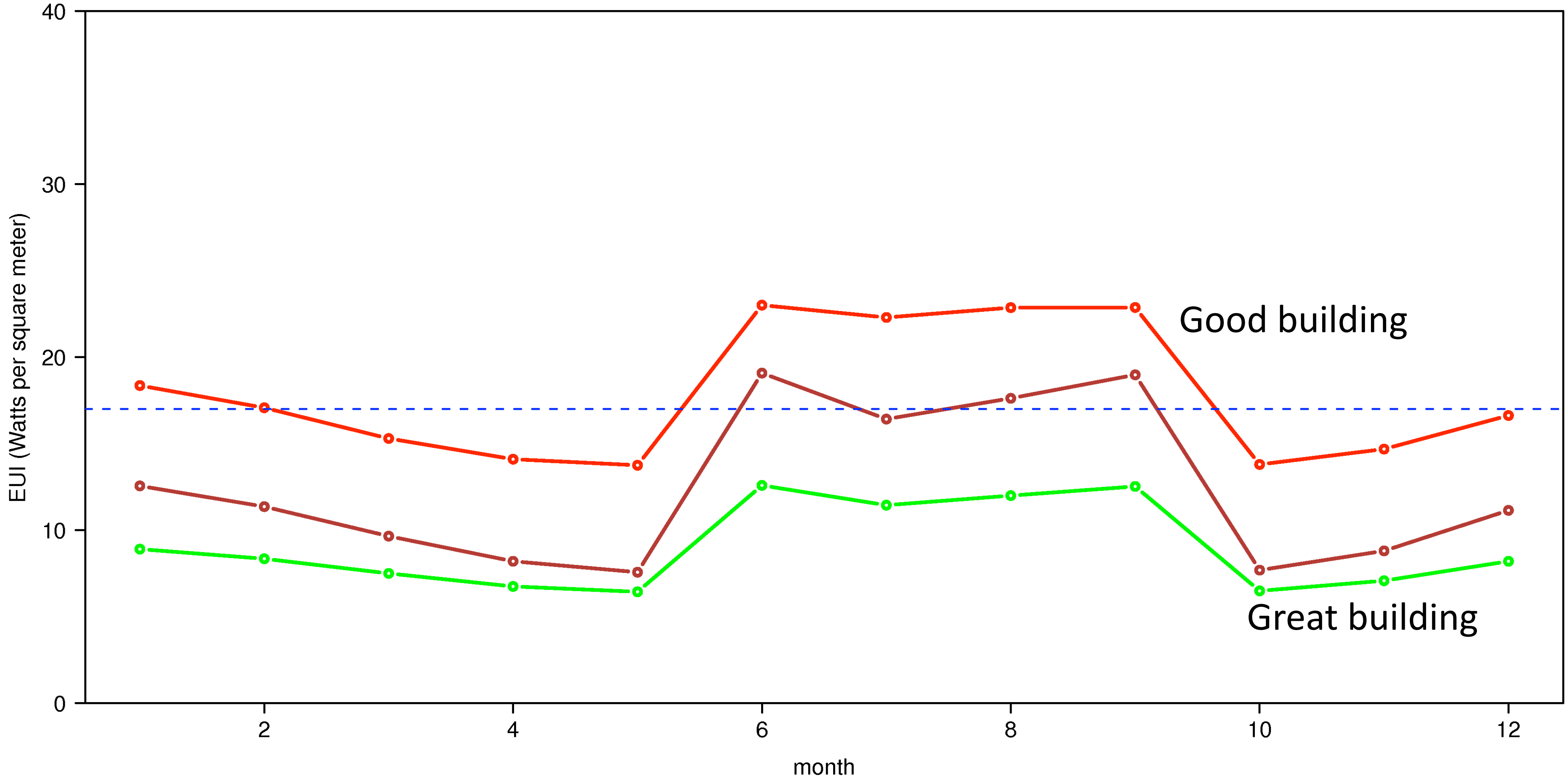
Uses **44 W/m²** site energy including transformer losses (initial prediction was **17**)

Average of other Oberlin College academic buildings: **47** W/m²

$420K PV rooftop array (4700 square feet, 45 kW actual peak production) provided about 20% of the building's energy in the first 2+ years of operation.

Oberlin prof. John Scofield has published data and analyses (and comments)

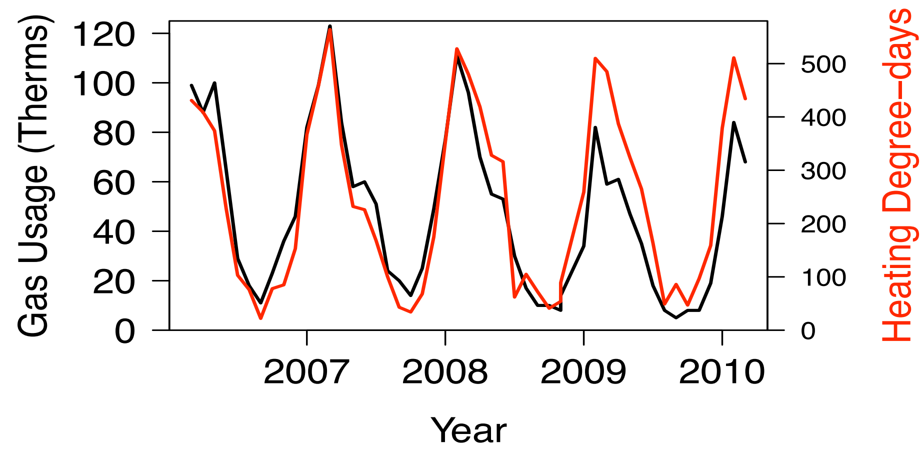
Oberlin Environmental Studies Building: were the initial goals physically possible?



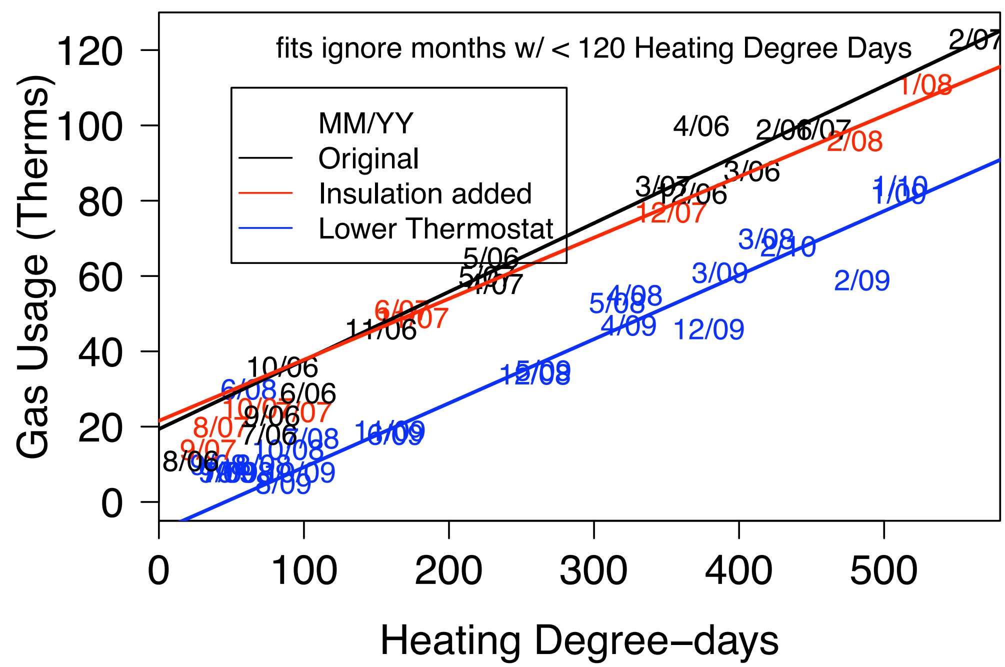
How much energy MUST a building use? **None**!

One way to reduce EUI is to reduce service levels (including pure waste):

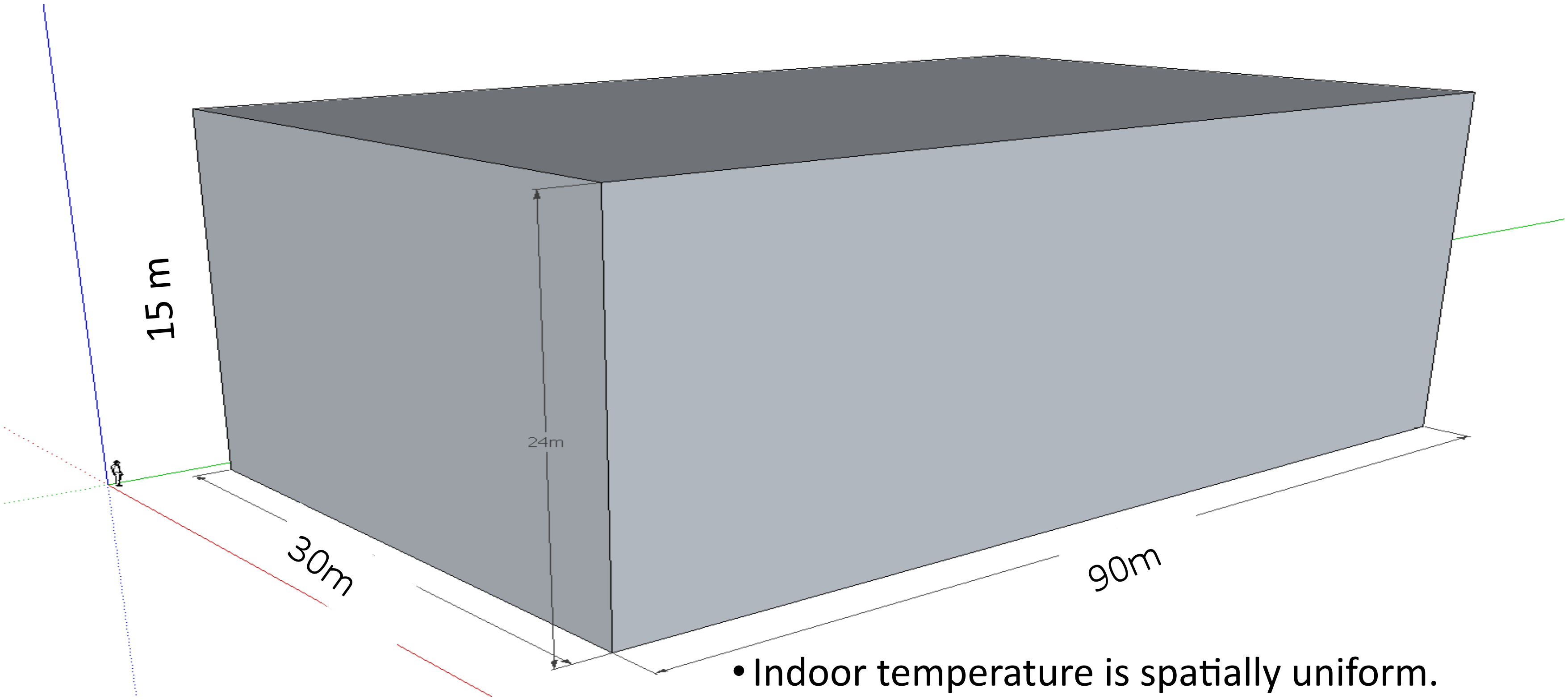
- Decrease average lighting levels;
- Turn off unused lights;
- Let indoor temperature get higher in summer, cooler in winter;
- Turn equipment off rather than keeping it in standby mode.



Suppose we want to maintain comfortable temperature, lighting, etc. How much energy do we need?



Extremely simple building energy model



- Indoor temperature is spatially uniform.
- Outdoor temperature varies sinusoidally.
- Daily lighting and plug loads are described by a quadratic function of time.

Model input parameters

Load (demand for power)

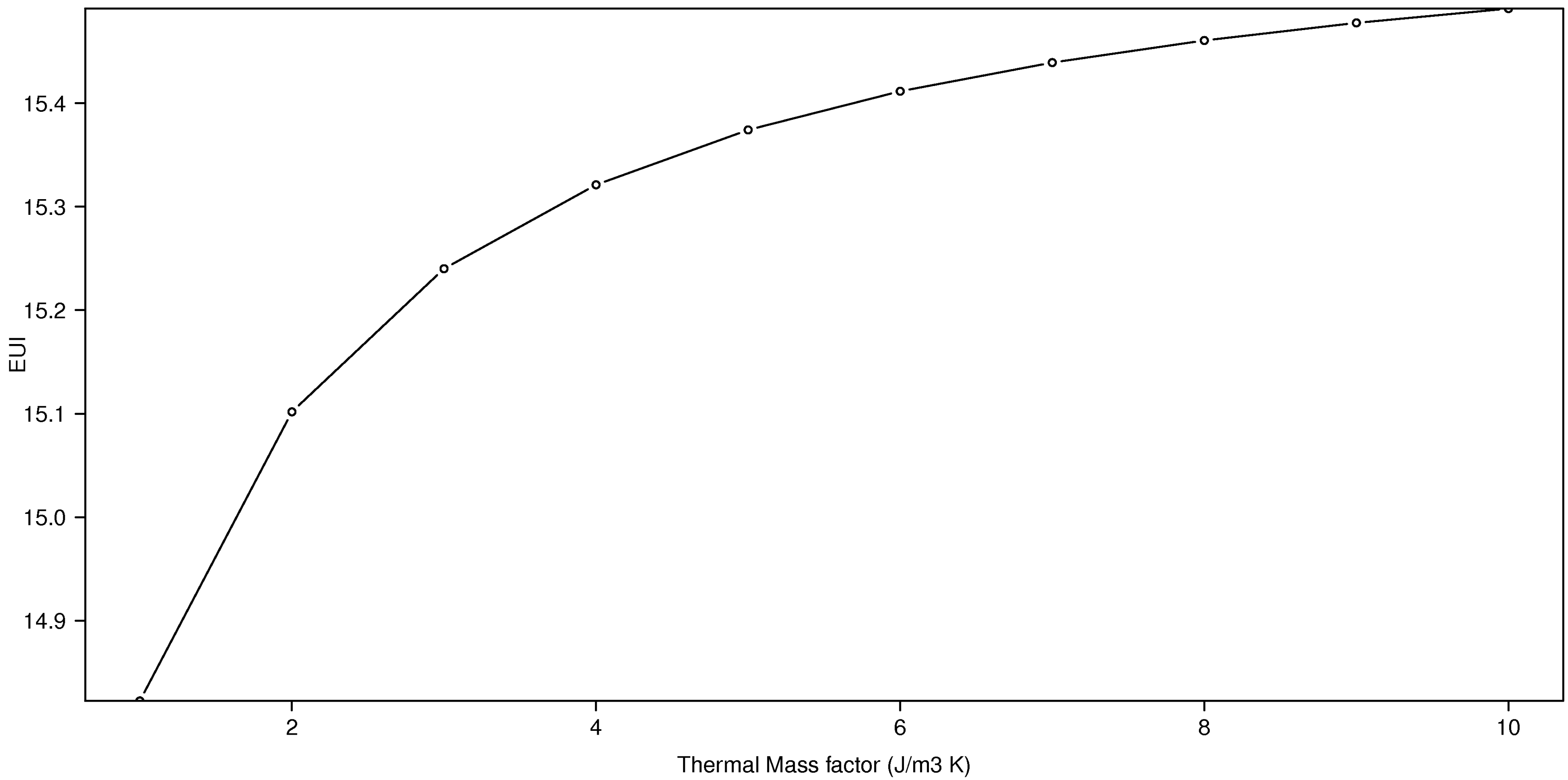
- Building dimensions
- R-value of exterior surfaces (averaged over walls, roof, windows, doors, etc.)
- Indoor temperature setpoint (daytime)
- Outdoor temperature by month (mean, diurnal variation)
- Lighting and plug load intensities

Power usage

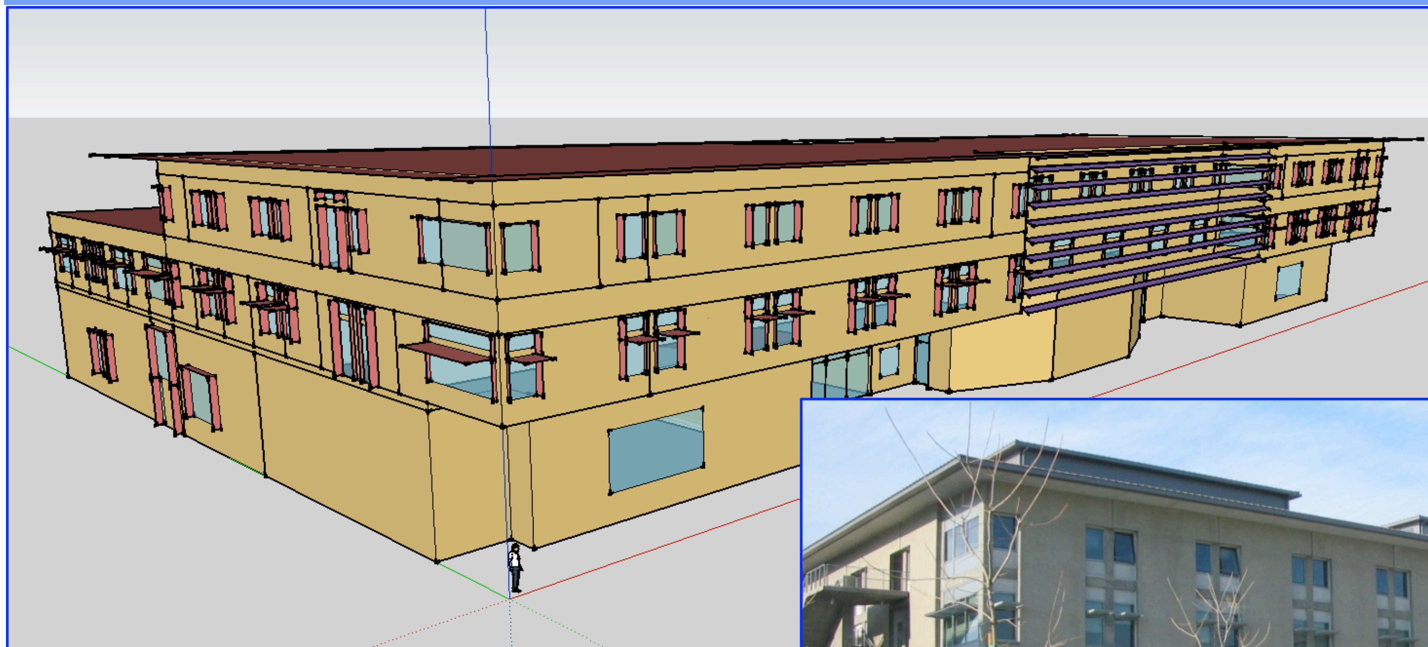
- Heating and cooling Coefficient of Performance
- Daylighting fraction
- Occupants:
    - Hours per week of occupancy
    - Floor area per occupant
    - Occupant activity level (power output from body heat)

$$\begin{aligned}\mathrm{EUI} = I_0 + \frac{1}{24A_\mathrm{f}}\Bigg[& C_\mathrm{th}(T_\mathrm{set} - T_\mathrm{drift}\,|_{t=24\mathrm{h}}) + \frac{12}{\mathrm{COP_h}}\left(\frac{A_\mathrm{ht}}{R}(T_\mathrm{set} - T_0) - A_\mathrm{f} I_0\right) \\ & - \frac{12\delta T\, A_\mathrm{ht}}{\pi \mathrm{COP_h} R}\Big(\cos\phi - \cos(\pi+\phi)\Big) \\ & + 8A_\mathrm{f}\left(\delta I_\mathrm{plug} + (1 - f_\mathrm{day})\delta I_\mathrm{light} - \frac{\delta I_\mathrm{people} + \delta I_\mathrm{plug} + \delta I_\mathrm{light}}{\mathrm{COP_h}}\right)\Bigg]\end{aligned}$$

EUI versus thermal mass



Model Representation of UC Merced Building



92,000 ft^2 (8500 m^2)

30 classrooms

100 offices

Auditorium

Open-plan office area

Fitting the Model

Software adjusts about 70 parameters.

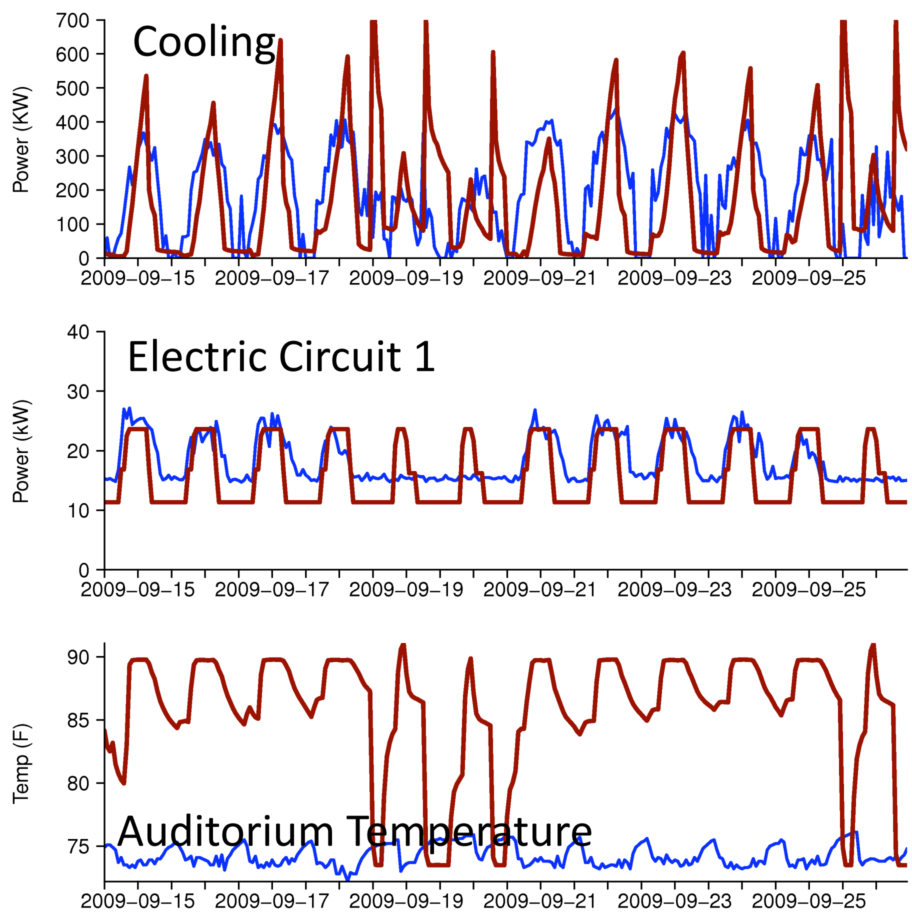
1500 model runs takes about 4-6 days.

The fit metric includes:

- cooling power,
- power on each of four electric circuits,
- heating power, and
- temperatures in classrooms, offices, auditoria, and hallways.
    - Temperature errors are converted into time-averaged power error (by incorporating the effect of building thermal mass and thermal relaxation time), so all errors can be expressed in units of power.

Constrained Optimization

Initial parameter estimates do not lead to good fits

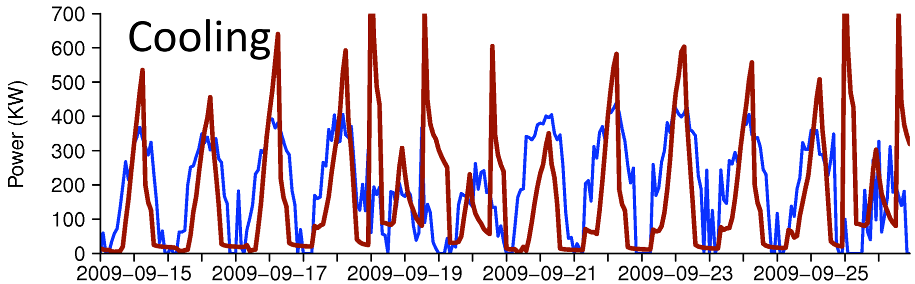


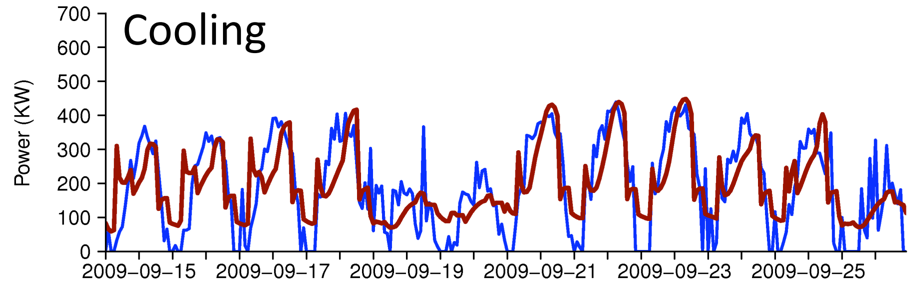
Blue = data, red = prediction

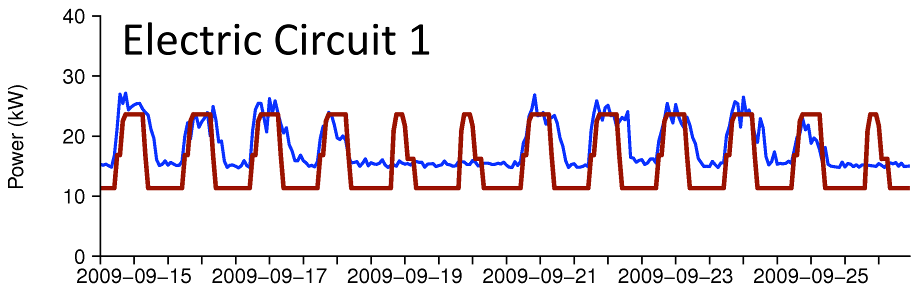
Constrained Optimization

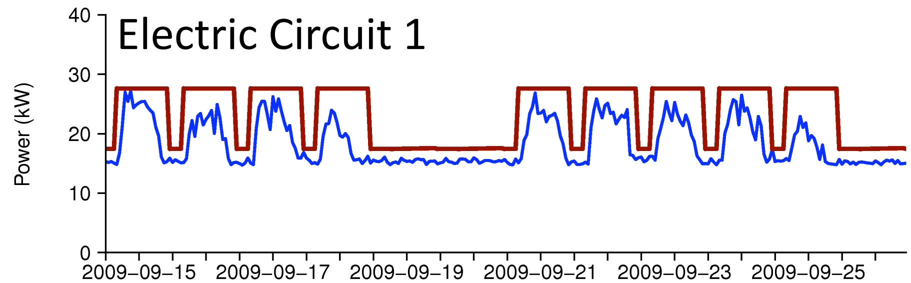
Initial parameter estimates do not lead to good fits

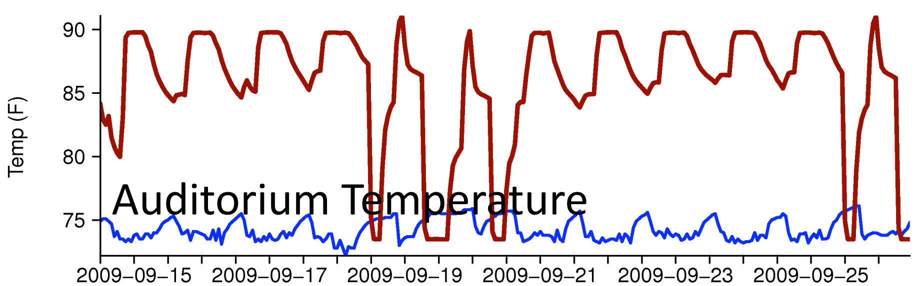
Optimized model fits much better

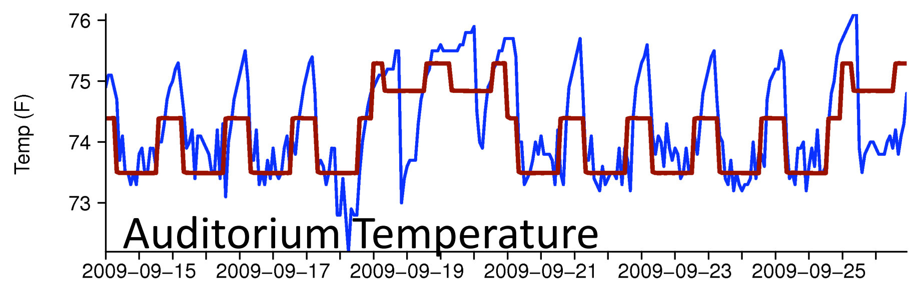








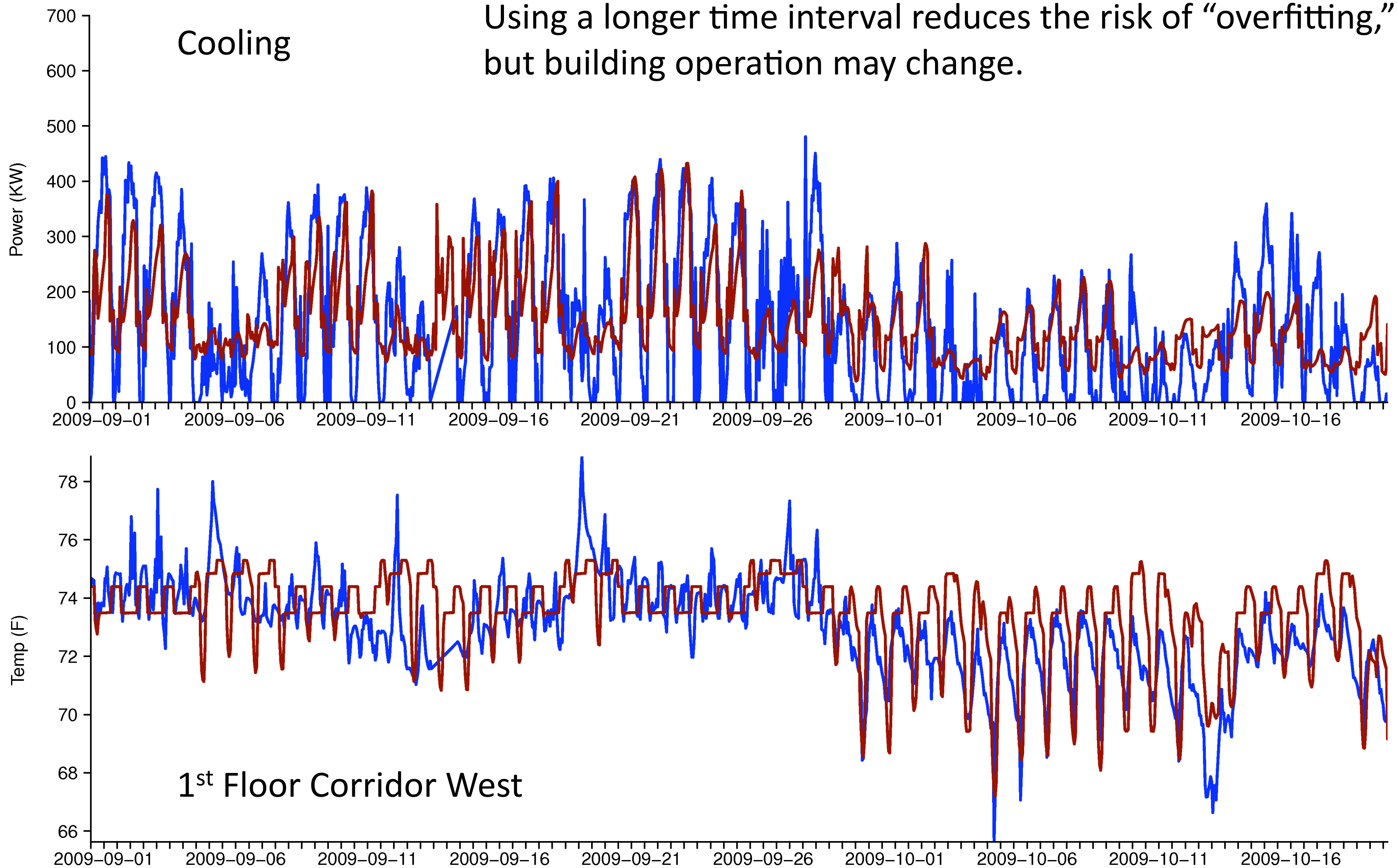




Blue = data, green = prediction

Final model for 2-month predictions

Using a longer time interval reduces the risk of "overfitting," but building operation may change.



Blue = data, red= prediction

Conclusions

- Major improvements are possible in principle.
- “Deep retrofits” will not be easy and may not be feasible

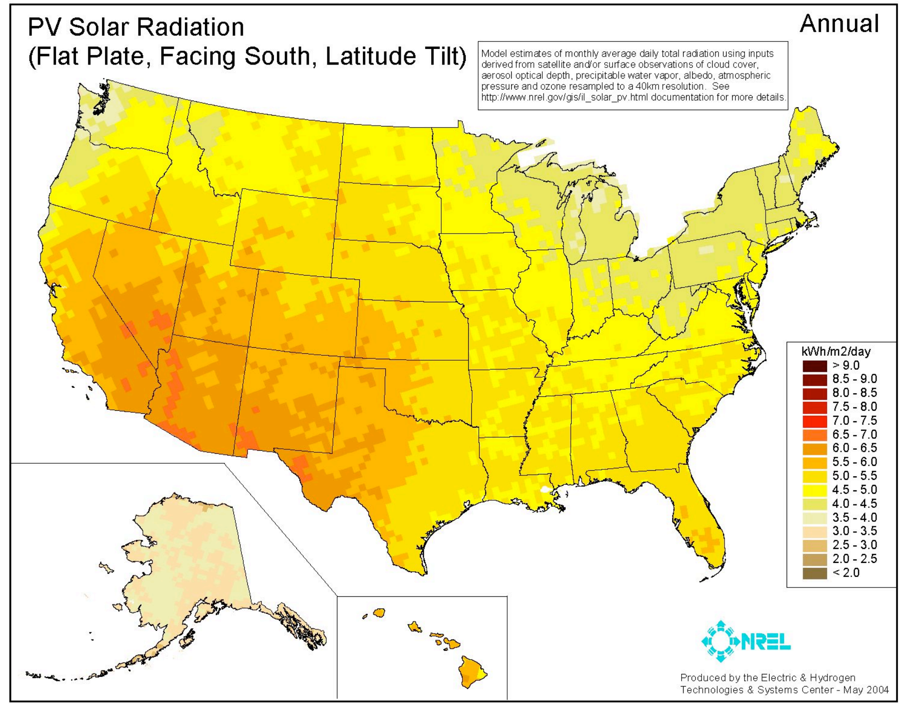
Extras

What's the problem?

Ambitious but attainable energy use intensity (EUI) in some climates:
20 W/m^2 average

Available PV power: 30 W/m^2 average
  Available solar radiation:
    5 $kW/m^2/day$ = 210 W/m^2
  PV efficiency after conversion losses: 0.14

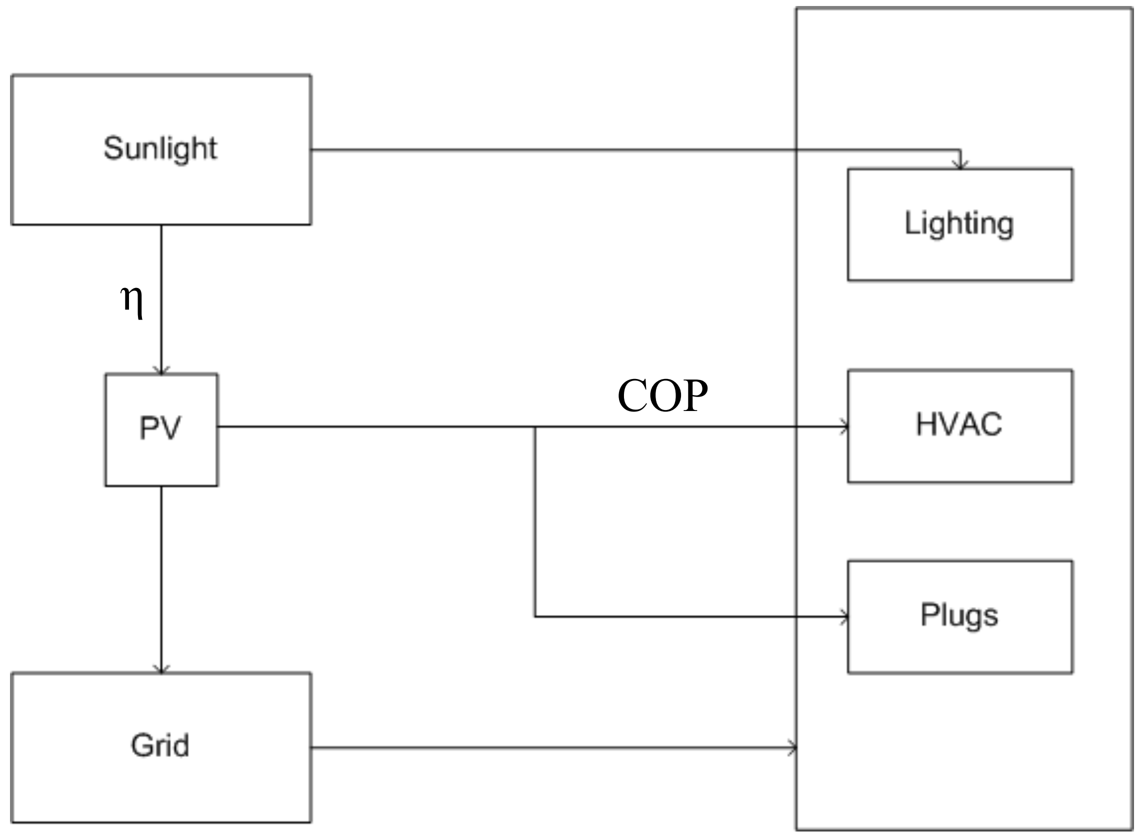
Available PV energy > energy needed. Does this mean that if we put PV on a fairly good building, it will be Net Zero Energy?



But: the m^2 in the EUI calculation is the floor area of the building. The m^2 in the PV calculation is the area of the PV array (the roof). For a two-story building, $A_{floor} = 2A_{roof.}$

Net-Zero Energy Buildings are attainable now, but only in Sprawlworld (1-story buildings, or 2-story buildings with exceptionally low EUI).

Rather optimistic logic: assume optimal use of sunlight



To get Net Zero Energy in a **multistory** solar building in most of the country, energy use intensity has to go down or PV efficiency has to go up (or both).

Net energy = energy produced – energy used

If we can do “net zero energy”, why not go even farther and make buildings net energy producers?

Bill Gates has it right (mostly)!

"Conservation and behavior change ***alone [emphasis added]*** *will not get us to the dramatically lower levels of* CO_2 *emissions needed to make a real difference. We also need to focus on developing innovative technologies that produce energy without generating any* CO_2 *emissions at all."*

From "Why We Need Innovation, Not Just Insulation", on thegatesnotes.com, 1/24/2010

But we already *have* technologies that produce energy without generating any CO2 emissions at all (wind, solar…). People just don't want to pay for them. But **if we can reduce energy use intensity by half**, we can enormously reduce the need for fossil fuel energy.

"Net Zero" isn't the right goal. "Low EUI" and "high-efficiency solar" are the things to go for.

All models are wrong; some models are useful. - George Box

Our model is **deliberately optimistic**:

- Humidity is ignored!
- Model neglects fan energy (and other energy costs of moving energy around)
- Model assumes unlimited, perfect energy storage: if we have "extra sunlight," we can use it later.
- Model includes a huge tracking solar rooftop array; virtually impossible. This leads to insolation being greatly overestimated (by a factor of 2 to 3).
- Heating COP=6 is at the upper limit of what is available.

We were barely able to make a ZEB in Minneapolis by using very optimistic assumptions. Does this prove that in real life, a large multi-story ZEB is impossible there?

Maybe, maybe not. There are some extra tricks (like thermal storage) that might help. But even if it is possible to build a large, multi-story ZEB, it will be very very hard.